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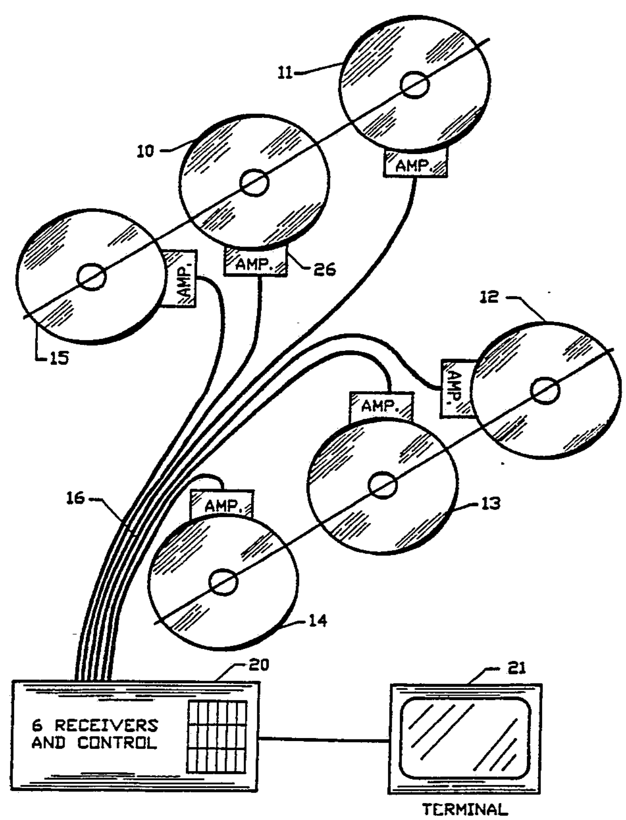
(54) Title: A RECEIVER FOR COMMUNICATIONS SATELLITE DOWN-LINK RECEPTION

(57) Abstract

A receiver (20) utilizing a plurality of smallparaboloid antennas (10-15) in lieu of a single large antenna of equal area, each antenna connected to a separate phase coherent heterodyne receiver channel includes a main channel and branch channels, the channels being summed to provide a carrier phase locked loop local oscillator signal that is distributed to all channels producing phase coherent IF signals in all the channels. These are summed to enhance the carrier margin of dB from the sensitivity threshold, of the system combining the receiver channels, to a level greater than that of the single antenna of equivalent area with its single receiver. The tendency toward cycle slipping near threshold is further reduced by providing predetection noise bandwidth filters in the IFs that are broader in the branch receivers than in the main receiver. The modulation spectra of the receiver channels are demodulated and summed to provide an output signal-to-noise ratio related to the sum of the effective areas of the plurality of smaller antennas. A digital phase locked loop bandwidth controller adjusts the sensitivity of the combined channel system to the received signal level, increasing the dynamic range of the system. The separate channel architecture of the receiver enables secure communications techniques including frequency diversity encoding, polarization diversity encoding, frequency reuse and data stream segment interleaving and multiplexing.



Description

A RECEIVER FOR COMMUNICATIONS SATELLITE DOWN-LINK RECEPTION

References to Prior Application

This invention is a Continuation-in-Part of an earlier application having the same title, filed 3 October 1985, Serial Number 783,697.

Origin of the Invention

This invention was made with Government support under NAS7-918 awarded by NASA. The Government has certain rights in the invention.

Background of the Invention

The commercial communications industry is planning a wide expansion of its facilities and it is possible that the number of satellites will increase from about 25 at this time to more than 110 at the turn of the century, if the present plans for increasing user services are implemented. Broadcasters and voice common carriers have been the dominant users of commercial communications satellites in the past. The extensive use of cable television would likely not have taken place if satellite transponders had not provided economical means to get the programming to local cable companies. Commercial television programming is relayed through the C-band transponders of the Hughes Galaxy I, the RCA Satcom 3-R, the Western Union Westar-5 and several other satellites. The transmission of audio broadcast signals is another area in which satellites are utilized. By using single channel per carrier techniques a single satellite transponder has the capability of relaying dozens of independent audio sources. With 10 dBW carriers leased from satellite common carriers, networks with nationwide coverage have been established that provide news and special programming of events through local radio stations. Regional broadcasters are also planning that by leasing a 10 dBW carrier, they can bypass local terrestrial station-to-transmitter links. Up-link antennas 5 meters in diameter and down-link antennas as small as 3 meters (9.85 ft.) are used. Satellite technology has also opened up the door to private networks, economical facility-to-facility data communications, Telex, Facsimilie, and Video Conferencing services. Satellite

communications is providing more and more relief to long-haul communications circuits; i.e., coaxial cable. Uplinking is possible from any location with relatively little power.

The critical element in a satellite link is the transponder power needed to perform these communications modes in all weather and under all conditions of loading. In lieu of research and development of better transponders, different methods of increasing the efficiency of a channel are being investigated. Video Conferencing, for example, implementing data compression techniques to trade off minimal picture degradation for greatly reduced data rates, is contemplated. An alternative to video compression is limited motion and freeze frame video. The use of statistical multiplexing and digital speech interpolation techniques can more than double a transponder's voice handling capacity. In addition, a variety of techniques for compressing the basic voice digitization down to 32 kilobits per second, or lower, are under consideration. Companded SSB can significantly increase the capacity of transponders already in orbit. Placing a compander in each voice circuit allows for a satellite transponder power per channel lower than for uncompanded FM. Typically an FM based system with 36 MHz of bandwidth can handle 2,800 one-way voice channels; companded SSB can boost the transponder's capability to 7,200 voice channels.

For the immediate future, however, the most noteworthy aspect of satellite technology is that it is moving to bring direct broadcast service (DBS) to the individual household. Direct broadcasting service in the US, downlinked on the 12.2 to 12.6 GHz $K_u$band is primarily aimed at millions of households that the cable industry does not currently serve. Over the last several years, however, the DBS concept has evolved into much more than a distribution system. What is envisioned now is enhanced quality video, menu driven and password protected program selection, and home data services.

To make the DBS installations feasible, certain technological barriers have to be overcome to make the services desirable and economical for the consumer. One challenge is raising the transponder power to lower the size and cost of Earth station dish antennas that the consumer must invest in. Up until now, some home owners have opted for the reception of satellite C-band TV signals that are intended for local cable distribution. Installing a TV receive-only C-band Earth station

is costly, but after one is installed there is a wide variety of programming available. However, court decisions may make it illegal to "pirate" these programs and programmers are undertaking to scramble more and more of their satellite transmissions. A receiver for this service must have the ability to unscramble the various scrambling or encoding algorithms and methods used in future systems.

The $K_u$band offers the prospect of an integrated home entertainment and information system that surpasses the performance of terrestrial and cable technologies combined. At a fixed carrier level, the signal-to-noise ratio achievable at the DBS delivery point depends on a suitable antenna and a low-noise temperature down converter as well as on the antenna's polarization, pointing error, and gain. However, antenna gain is directly related to the dish size. Hence, to keep the dish small for ease of installation and for concealment, which is becoming a requirement in an increasing number of localities, the need for placing new higher power transponders in orbit becomes imperative unless some alternative system, such as the invention described herein, is used to receive the downlink. In the invention, the dish antennas do not have to be mounted on the roof; they can be small enough to be concealed under the roof in an average dwelling or office building, reducing or eliminating moisture and weather effects which can cause attenuation at K_u band.

The novel receiver employs a combination of principles governing the reception of weak signals and the combining of outputs of antennas and receiver arrays, as well as signal processing for digital and analog signals. The prior art is represented by applicant's prior patent No. 4,186,347 which is related to telemetry receiver carrier combining of a plurality of separate receiving systems, but which is limited to carrier sensitivity improvement of the array that is less than the ratio of total antenna array aperture to main receiver antenna aperture. The present invention defines receiver implementations for equal or unequal aperture antennas, in combination with other novel features described herein, to obtain carrier sensitivity improvement that is greater than the ratio of total antenna array aperture to main receiver aperture, and provides a correlated demodulated output signal that represents the total antenna array aperture. The unequal aperture case in which antennas of unequal size may be used, is des-

cribed with reference to performance characteristics of the same system, but it is another embodiment.

Summary of the Invention

This invention provides a high sensitivity receiver for electromagnetic radiation reception particularly in the C-band, S-band, X-band and K_u band which are the bands now in use or planned to be utilized for transmission of commercial communications services and home entertainment and data services. The novel receiver lends itself to reception of several different modes of transmission and program encryption or scrambling, and is amenable to tracking any signal having a lower power level inserted carrier, or a pilot signal such as is used in FM or single sideband. Any type of modulation on the signal or signals that is in turn phase modulated onto a phase stable microwave or RF carrier with a residual carrier whose level is a few percent of the total signal power, can be received and provided to the user for demodulation and detection or presentation. This mode of transmission allows the use of the most sensitive receiving system; i.e., the phase coherent system espoused in this invention. Note that the lower power level inserted carrier or pilot signal cases will provide a less sensitive system than the phase modulated system, for the same received signal level conditions. This high sensitivity, high dynamic range receiving system which utilizes a plurality of smaller antennas in lieu of a large antenna, has a carrier sensitivity better than, and a demodulated signal-to-noise ratio equal to, the larger antenna and single receiver having an equal effective area. The receiver uses a phase stable fixed frequency local oscillator signal for the first heterodyne mixer so that all branches of the receiver including the main receiver and branch receivers 1 through N have first IF signal outputs that are at the same fixed frequency, except for the frequency diversity embodiment to be described later. These signals are at a low level and are amplified in a first IF amplifier in the main receiver and N branch receivers, and are applied to a heterodyne mixer in the main receiver which receives a local oscillator signal controlled by a first phase locked loop. This phase locked local oscillator signal is distributed to the N branch receivers and applied to the second heterodyne mixer of each receiver. The main

receiver and the branch receivers include a third heterodyne mixer and a third IF amplifier. The local oscillator signal applied to the third heterodyne mixer in each branch receiver is controlled by a phase locked loop in each branch receiver. The local oscillator applied to the third heterodyne mixer in the main receiver is a fixed phase stable frequency.

The outputs of the main receiver and the N branch receivers at the third IF amplifier output are fed to a carrier summing junction where the carrier signals are combined in phase to yield a carrier sensitivity greater than a single receiver and large aperture antenna with equal effective area.

A separate wide bandwidth third IF amplifier and phase detector in the main receiver and each branch receiver provide coherent demodulation of the signal. All receiver signals are coherently summed in a separate summing junction to provide the data spectrum output to the user. The modulation group delay of each branch receiver is matched to the corresponding main receiver group delay to optimize the signal-to-noise ratio of the correlated modulation output signal.

A digital implementation of the receiver allows the carrier phase locked loop bandwidth of the summed receiver system to be automatically adjusted in accordance with the carrier predetection signal-to-noise ratio such that the receiver can accommodate the signal-to-noise ratio degradation due, for example, to atmospheric effects.

In operation, the receiver is tuned to the carrier frequency of the satellite service by setting the frequency of the first local oscillator signal at the first heterodyne mixer. The first local oscillator frequency is set to receive any one of the several transmissions provided by the satellite service by selecting the matching phase stable fixed frequency source. This first local oscillator signal is set either manually or by remote control and provides the first IF output signal when heterodyned with the tuning reference frequency. Fixed frequency phase stable references are mixed with a phase locked loop signal to provide the local oscillator signal controlled by a carrier first phase locked loop, to the second heterodyne mixer in the main receiver and to the second heterodyne mixers in the N branch receiver channels (except for frequency diversity reception). This heterodyne process provides the second IF output signal in the main and N branch

receivers. After heterodyne conversion in the third heterodyne mixer with a fixed frequency phase stable reference in the main receiver, the carrier third IF is summed with the N branch receiver carrier third IFs to provide coherently summed carriers plus carrier loop predetection receiver noise of the main receiver and the N branch receivers. The bandpass limited output of the summed main receiver carrier third IF amplifier is analog-to-digital (A/D) converted and compared in phase with the quadrature phase of the coherent A/D converted detector reference frequency, sampled every T_1 time interval and averaged over each T_1 to provide a measure of the phase error (in digital form) in the phase locked loop for each T_1. The time between samples T_1 is a function of the received signal level. This averaged measure of phase error for each T_1 in digital form is applied to a software tracking filter whose output causes a numerically controlled oscillator to change phase, and when mixed with the main receiver fixed reference frequencies, provides phase lock with the received carrier frequency. Analog techniques can also be used to accomplish the same functions.

For frequency diversity reception, a different phase stable fixed frequency oscillator, or frequency synthesizer if frequency agility is required, would be used for each N branch receiver in place of the second fixed frequency reference used in the main receiver to provide a second local oscillator frequency offset in each of the N branch receivers' second local oscillator to match the frequency offset relative to the main receiver of each of the diverse received frequencies. See Figure 4 for a block diagram of the receiver.

The patent literature on arraying receivers, notably patent No. 4,186,347 shows that after the second IF predetection filters which are equivalent to the third IF carrier predetection filters in the instant invention, the ratio of the noise bandwidths of the branch receiver IF carrier predetection filters to the main receiver IF carrier predetection filter noise bandwidth is recommended by design to be one. However, in the instant invention it is required that the noise bandwidth of the branch receiver IF carrier predetection filters be wider by a factor k than the main receiver IF predetection filter where k is nominally 9 for equal aperture antennas and 9 for unequal aperture antennas. This relationship will be described with reference to Figure 4. It was found by theory and experimentation that for operation near

receiver threshold sensitivity, increasing the predetection bandwidth of the branch receivers improves the immunity to cycle slipping and loss of lock in the summed receiver system.

The architecture of the summed receiver system, using a plurality of channels, lends itself well to encryption of program material by frequency diversity either singly or in combination with other scrambling or encoding techniques. In frequency diversity, a television transmission or other data, particularly imaging data, are split up among the several receivers, each operating at a separate frequency making up the summed system and are reassembled by keyed decoding functions with the key being changeable and known only to the subscribers. Since the carrier signals are coherently summed and demodulated, they can each carry discrete segments of the modulation. The frequency diversity encryption method is adaptable to the widely used aerospace ,generally post-detection, encoding methods that are fully developed. These include pseudonoise coding and interleaved Reed-Solomon coding, as well as the simpler multiplexing algorithms. The proper encoding algorithm can produce improved data since error correction, data compression and dropout compensation can be employed.

Another aspect of the receiver system of this invention is its adaptability to frequency reuse; i.e., transmitting and receiving separate information on orthogonal polarizations of the same signal. As an illustration, in this implementation, the six channels of the receiver are split up into three antennas each with orthogonal polarization output ports. In this manner, six different carriers can be used for frequency diversity with each antenna having a polarization diversity capability, enabling further possibilities for secure communications. The novel receiver is uniquely adaptable to all the modes of satellite transmission that are in use or planned for the near future.

Brief Description of the Figures

The novel features of the invention are set forth in the drawings of which:

Figure 1 is a conceptual drawing of the receiver installation illustrating the equal or unequal aperture antennas and the remotely located elements of the novel receiving system as well as the operator

and display elements.

Figure 2 is a schematic block diagram of the receiver showing the essential elements of the receiver including the front end, the receiver channels, the summing methods for the carrier and the modulation spectrums when taken in combination with Figure 3 which shows the digital controller.

Figure 3 is a block diagram of the digital controller which applies to both Figures 2 and 4 for controlling the bandwidth of the phase locked loop local oscillator.

Figure 4 is a schematic block diagram of the frequency diversity embodiment of the receiver, illustrating also the polarization diversity and frequency reuse capabilities of the receiver.

Figure 5 is a graph showing the effect on the carrier margin of widening the noise bandwidth of the branch receiver third IFs for equal apertures in preventing loss of phase lock at very low signal levels.

Figure 6 is a graph showing the effect of increasing the carrier margin by combining the outputs of a plurality of equal aperture antennas and their receiver channels.

Figure 7 is a graph showing the effect on the carrier margin of widening the noise bandwidth of the branch receiver third IFs for unequal apertures in preventing loss of phase lock at very low levels.

Figure 8 is a graph showing the effect of increasing the carrier margin by combining the outputs of a plurality of unequal aperture antennas and their receiver channels.

Description of the Preferred Embodiments

The receiver embodiments to be described in the following have in common the use of equal or unequal aperture antennas, each having a separate receiver channel with the channels being summed after the third IF amplifiers in each of N receiver channels. The signal carriers are

summed in this system in such a manner that the signals are coherently additive while the noise is summed in an rms fashion. The point of summing is after the predetection IF amplifiers for the carriers while the modulation spectrums are summed in another junction at baseband. In the embodiments to be described, only one branch receiver A of N possible branches is shown because the branch receivers are identical except for possible differences in group delays, and differences in configuration for frequency and polarization diversity implementations.

Referring now to Figure 1, the antenna paraboloids for the receiver include the main receiver antenna and branch receiver antennas 11 through 15. The distance between the main antenna and the branch antennas is dependent upon the antenna enclosure, or if the space is unlimited for antenna installation, the branch antennas can be located for spatial diversity to compensate for fading due to atmospheric propagation effects. The paraboloids are nominally a few feet in diameter providing convenient light weight packages that can be easily handled by one man for installation in the upper story of a residence or office building where they can be concealed and protected from the environment. Low voltage DC is provided for powering the wideband amplifiers at the base of the antenna. Coaxial lines 16 connect the antennas' amplifiers to the summing receiver at a location that could be hundreds of feet away. Delay line loops in the coaxial cables provide for tailoring the group delays in the branch antennas relative to the main receiver as a rough approximation. Phase shifters in the receiver channels perform the vernier group delay adjustments. Once set, the group delays in each receiver channel remain the same. The receiver package in this embodiment is a five branch channel and one main channel receiver having fixed frequency selection for tuning control. Depending on the service being rendered by the satellite service; for example, television or facsimilie, an appropriate display device or terminal and peripheral device 21 is operated from the six channel receiver.

Figure 2 shows the conceptual block diagram of the main channel and one branch channel. All of the branch channels are essentially the same as the A channel. The wideband amplifiers at the antennas 23 provide sufficient bandwidth to accommodate the desired reception band. These amplifiers are designed to be low noise within the state of the

art. Any signal in the frequency range is applied as one input to the first heterodyne mixer 24. The other input to the mixers 24 is the first local oscillator signal which is a source 25 of fixed frequency phase stable signals, manually or remotely settable for receiver tuning. The output of the first mixers 24 are applied to first IF amplifiers 26. These amplifiers furnish the first intermediate frequency outputs from the antenna area for each receiver channel. These signals are applied to second mixers 27 in the receiver package located remotely from the antenna area for each receiver channel. The second heterodyne mixers 27, 27A through N have a local oscillator which coherently tracks the phase of the received carrier at the first IF frequency with a carrier tracking loop in the main receiver. This tracking loop includes the third IF filters 29, the carrier summing junction 30 and the third IF amplifier 31 in the main receiver.

Referring to the main receiver third IF amplifier 31, this amplifier has a limited output and a linear output. The linear output is applied to a coherent amplitude detector and AGC circuits which operate in a conventional manner. The limited output provides a carrier component which varies with received carrier level which in turn, provides change in closed loop tracking bandwidth with change in signal level as described herein. The reference signals shown are all standards for frequency and are phase stable within the state of the art for high quality equipment. Refer to Figure 3.

The bandpass limited output of the summed main receiver third IF amplifier 31 is analog-to-digital (A/D) converted and compared in phase with the quadrature phase of the coherent A/D converted second reference frequency in detector 32, sampled every time interval T_1 and averaged over each T_1 time interval to provide a measure of the phase error in digital form in the phase locked loop for each T_1. The time between samples T_1 is a function of the receiver signal level. This average measure of phase error for each T_1 time interval is applied to a software or firmware tracking filter whose output causes a numerically controlled oscillator (NCO) 34 to change phase. When mixed with the main receiver fixed reference frequencies, the NCO with D/A provides phase lock with the received carrier frequency. The bandpass limited carrier third IF output; i.e., summed coherent carrier plus receiver noise, is constant in level, with the receiver predetection noise

component decreasing and the carrier component increasing as the received satellite signal level increases. The time interval between samples T_1 is controlled by the carrier component S_{c1} of the bandpass limited third IF output with the time between samples T_1 decreasing as S_{c1} increases. The carrier component S_{c1} is represented by the average value of S_{c1} + noise, a digital value, which results from digital detection of the A/D converted bandpass limited output of the main receiver carrier third IF amplifier, with the in-phase A/D converted detection second reference frequency for the main receiver phase locked loop. At the design point, the average value of $S_{c1} + N$, a digital value, provides a specified value T_1 which in conjunction with other loop parameters, determines the design point closed loop bandwidth of the main receiver carrier phase locked loop. As the receiver input signal level increases, the average value of $S_{c1} + N$ increases. This reduces T_1 or time between samples which in turn increases the closed loop noise bandwidth of the main receiver carrier phase locked loop. The N branch receivers utilize similar techniques to provide in each branch receiver a local oscillator controlled by a carrier phase locked loop to the third heterodyne mixer with fixed frequency phase stable references and set to the same frequency as reference frequency 1 in the main receiver to achieve phase lock and track out any differential phase effects. The $S_{c1} + N$ is provided by detecting the limited output of the third IF amplifier with the reference frequency, in detector 35. The average value is applied to the sample and average 36 which controls the value T_1 which is inversely proportional to the carrier component S_{c1}. A similar situation exists in the branch receiver A where the $S_{c2} + N$,carrier signal plus noise, is applied to the sample and average 36A such that the sampling period T_2 is inversely proportional to the carrier component S_{c2}. The computation delay 37 provides a delay and controls the time for each T_1 when the phase of the NCO in the main receiver is changed. Another unique element of the receiver is the demodulator signal spectrum summing which occurs after the third mixer, emanating from the second IF distribution amplifier and IF filter, followed by a third IF amplifier and phase detector, the output of which is the demodulated signal spectrum. These outputs from the main receiver and the N branch receivers are coherently summed in a signal summer 41. This summing circuit provides a demodulated

signal at a carrier margin enhanced over what would be available relative to the signal to noise ratio of a single antenna and receiver system having the same aperture area.

Reference is directed to Figure 4 which shows an embodiment of the invention for frequency diversity, frequency reuse for bandwidth conservation by transmitting information on orthogonal components of the same frequency carrier, and a polarization diversity mode of operation. It can be seen from Figure 4 that the architecture of the receiver is substantially the same as the receiver of Figure 2 except that in the main receiver the phase locked receiver controller output is applied to a first mixer 42 which receives a fixed frequency reference that is of a high frequency so that the sum of the two inputs to the mixer 42 is equal to the local oscillator frequency desired to tune the second mixer 43 to heterodyne with the output signal from the first IF output amplifier emanating from the antenna area to produce the second IF signal which is coherently detected as described for Figure 2. The difference between Figure 2 and Figure 4 is in the branch receivers A through N. Each receiver operates at a different frequency, yet they remain coherent with the main receiver system by virtue of the fact that the main receiver controller phase locked loop output is applied to a mixer 44 which also receives a phase stable fixed frequency reference so that the output of the mixer 44 is a frequency offset from the main receiver frequency and differing from the input signal from the first IF amplifier of the branch receiver, emanating from the antenna area, by the second IF frequency. The bandpass filters 45 and 46 establish the bandwidth limit and select the proper frequency output of the mixers 42 and 44. It will be appreciated that this implementation allows each branch receiver to operate at a different frequency while maintaining phase coherence with the main carrier signal and enables summing of the third IFs which are at the same frequency to provide the advantages previously described for the summed receiver configuration. The demodulated signal spectrum from each receiver is applied to a modulation summing circuit as in the embodiment of Figures 2 and 3. It is apparent that since the modulation spectrums can be summed, different segments of the modulation can be transmitted on separate carriers received by separate receivers. These separate carriers can further be encoded with the same or separate codes and decoded after the summing circuit 41,

Figure 3. Thus, a two dimensional encoding or scrambling system is provided for secure communications.

Another embodiment of the versatile receiver adapts it to bandwidth conserving frequency reuse modes of transmission. With reference to Figure 4, with Figure 3, each antenna can employ an orthomode feed 51 such that the main receiver channel can receive the signal from one of the orthogonal polarization ports while a branch receiver can receive orthogonal polarization signals from the other.

Also, in this embodiment, two of the branch receivers can receive the signals from orthogonal polarization ports of the second antenna. This technique can be expanded to a third antenna with orthogonal polarization ports and two additional branch receivers. This configuration is also advantageous for secure communications wherein segments of the data spectrum can be multiplexed on orthogonal polarizations of the carrier according to an algorithm. The combination of frequency diversity as described earlier and polarization diversity is possible wherein a carrier frequency of left circular polarization and another carrier offset therefrom can have right circular polarization, both carriers containing modulation or encoding segments thereof, can be combined in the receiver of Figure 4 and Figure 3, thereby providing two additional dimensions for encoding or encryption algorithms.

Referring to Figure 5, we see a plot of phase noise in degrees rms in the carrier phase tracking loop versus initial main receiver carrier margin. We note that for the main receiver alone at low carrier margins of 0 to 10 dB, the phase noise is greater than 22 degrees and cycle slipping in the carrier tracking loop will occur. The plot shows that with the main receiver and one branch receiver with equal aperture antennas coherently summed and the bandwidth of the branch receiver third IF filter 9 times the bandwidth of the main receiver third IF filter, the gain in carrier margin is 6.6 dB at low carrier levels and cycle slipping for the coherently summed receivers will not occur at a carrier level which represents an initial 4 dB carrier margin for the main receiver alone. This represents a basic difference of the invention over the prior art in which this principle; i.e., differential bandwidth filtering was not recognized or utilized.

Reference to Figure 6 shows another graph of carrier margin

improvement over a single equivalent area antenna for an array of from 2 to 6 antennas for k = 9. Consider the case shown and described in Figure 5 for a main receiver and one branch receiver with equal aperture antennas. A single equivalent antenna with its receiver would have twice the area which provides 3 dB more carrier margin than the main receiver with its smaller antenna. However, as shown in Figure 5, the equal aperture array has 6.6 dB more carrier margin than the main receiver alone with its antenna. Consequently, the improvement or "enhancement" in carrier margin for two equal aperture antennas with their receivers is 6.6 minus 3 or 3.6 dB relative to a single equivalent area antenna with its receiver as shown in Figure 6. This relative carrier margin improvement increases slightly for a main receiver and two branch receivers (3 antennas) arrayed and decreases to 2.6 dB improvement for 6 antennas with their receivers arrayed.

Referring to Figure 7 as an example, we see a plot of phase noise in degrees rms in the carrier phase tracking loop versus initial main receiver carrier margin, for the case where the branch receiver antenna diameters are 0.6 the diameter of the main receiver antenna, and the aperture efficiencies and receiver noise temperatures are equal. We note that the main receiver alone, at low carrier margins of 0 to 10 db, has a phase noise greater than 22 degrees and cycle slipping will occur in the carrier tracking loop. The plot shows that with the main receiver and one branch receiver coherently summed, and the bandwidth of the branch receiver third IF filter 9 times the bandwidth of the main receiver third IF filter, the gain in carrier margin is 4.64 db at low carrier levels, and cycle slipping for coherently summed receivers will not occur at a carrier level which represents an initial 5.5db carrier margin for the main receiver alone. This represents a basic difference over the prior art in which this principle was not recognized and not utilized.

Reference to Figure 8 shows another graph of carrier margin improvement over a single equivalent area antenna for an array of from 2 to 6 antennas for k = 9 and the diameters of branch receiver antennas equal to 0.6 the main receiver antenna diameter. Consider the case shown and described in Figure 7 for a main receiver and one branch

receiver with an antenna aperture of 0.36 the main receiver antenna. A single equivalent antenna with its receiver would have 1.36 times the area which provides 1.34 db more carrier margin than the main receiver would have with its smaller antenna. However, as shown in Figure 7, the two-antenna array has 4.64 db more carrier margin than the main receiver alone with its antenna. Consequently, the improvement or "enhancement" in carrier margin for the two antenna array is 4.64 minus 1.34 or 3.3 relative to a single equivalent area antenna with its receiver as shown in Figure 8. This relative carrier margin improvement increases slightly for a main receiver and two branch receivers (3 antennas) arrayed and decreases to 2.4 db improvement for 6 antennas with their receivers arrayed.

Although the novel receiver embodiments show paraboloidal antennas, other types can be used; e.g., disk-on-rod, offset, shaped reflector, without departing from the teachings of the invention.

Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications and variations may readily occur to those skilled in the art and consequently, it is intended that the claims be interpreted to cover such modifications and equivalents.

WHAT IS CLAIMED IS:

1. A receiver for satellite communications, which comprises:

a plurality of antennas receiving at least one modulated signal having a carrier frequency;

a plurality of heterodyne receiver channels including a main receiver channel and at least one branch receiver channel, said receiver channels including a mixer, and a carrier phase locked loop local oscillator coupled to said main receiver channel and to said at least one branch receiver channel at said mixer, said receiver channels each connected to one of said plurality of antennas for amplifying and converting said carrier signals to a wideband intermediate frequency modulation spectrum output, and a narrow band carrier output, said outputs being phase coherent with said main receiver channel and said at least one branch receiver channel;

means for setting the carrier predetection noise bandwidth of the branch receivers to a value of greater than one times the value of the main receiver carrier predetection noise bandwidth, coupled to said main receiver and each of said branch receivers;

a first summing junction for combining said narrow band output of each of said plurality of heterodyne receiver channels into a single narrow band carrier + noise spectrum, said narrow band output coupled to said phase locked loop local oscillator;

detector means connected to said wideband intermediate frequency output for detecting the modulation spectrum including at least one data signal from each of said plurality of receiver channels;

a second summing junction for combining said wideband intermediate frequency detector output of said plurality of receiver

channels, said second summing junction having an output;

terminal means connected to said second summing junction output adapted to distribute the modulation spectrum including at least one data signal to at least one peripheral device;

whereby the carrier sensitivity margin is enhanced in accordance with the number of branch receiver channels and the immunity to cycle slipping at low carrier sensitivity margins is enhanced in accordance with the branch-to-main receiver channel differential predetection noise bandwidth, and the signal-to-noise ratio of the modulation spectrum is improved in accordance with the number of branch receivers.

2. A downlink receiver as described in claim 1, further comprising:

controller means for varying the bandwidth of the carrier phase locked loop in accordance with the received signal level to control the sensitivity of the receiver with signal level.

3. A digital phase locked loop bandwidth controller for receivers, which comprises:

a receiver having a limited intermediate frequency amplifier output, the limit level being the optimum performance point of the receiver dynamic range, said amplifier having a narrow band signal + noise output at intermediate frequency;

a first analog-to-digital converter changing said limited intermediate frequency amplifier output signal-to-noise to a digital value which includes the time varying sinusoidal carrier signal phase;

a first frequency standard having an output signal phase shifted

90 degrees with respect to said intermediate frequency amplifier output carrier signal and converted from analog to digital values which includes the time varying sinusoidal frequency standard phase;

a correlator having a digital value output with a + or - sign bit which represents the phase error relative to 90 degrees, between the intermediate frequency amplifier output carrier signal and the orthogonal frequency standard signal;

a second frequency standard signal converted from analog to digital values, in-phase with the carrier signal contained in the analog-to-digital converted bandpass limited output of the intermediate frequency amplifier;

a second correlator having a digital value output which represents the S_{c1} carrier component + noise correlation between the intermediate amplifier output carrier signal and the in-phase frequency standard;

an averager receiving the phase error from the phase error correlator and receiving the S_{c1} component from the in-phase correlator, producing a sampling of the phase error at intervals inversely proportional to the magnitude of S_{c1} at an output of the in-phase correlator, the averager providing the phase error averaged over each sampling interval as a digital number with a + or - sign bit as an output;

a tracking filter connected to said averager output, establishing the response time of the loop, said filter having an output;

a numerically controlled oscillator changing the phase of the local oscillator of the receiver, in accordance with the phase error represented by the average magnitude of the signal + noise over the sampling period; and

delay means receiving said tracking filter output, for controlling the time when the phase error averaged over each sampling

interval is applied to said numerically controlled oscillator, connected to said oscillator.

4. A receiver as defined in claim 2 wherein each branch receiver employs a phase locked loop bandwidth controller in a second phase locked loop preceding the third intermediate frequency amplifier, whereby the bandwidth of the phase locked loop is varied in accordance with signal level.

5. A receiver as described in claim 1 wherein each branch receiver receives a different carrier frequency, and a different local oscillator frequency offset from the phase locked loop local oscillator of the main receiver by a mixer receiving the output from an offset phase stable frequency generator, and the local oscillator of the main receiver, producing an intermediate frequency that is the same in all receiver channels.

6. A receiver as described in claim 1 further comprising:

an orthomode transducer receiving left or right circular polarization in said main receiver channel and its opposite in said at least one branch receiver channel whereby said branch receiver channel receives a modulation different from the main receiver on an orthogonal polarization of the same carrier frequency without loss of carrier sensitivity margin.

7. A frequency diversity receiver for secure communications, which comprises:

a plurality of antennas receiving a plurality of modulated carrier signals, each carrier having a different frequency and the same or different data modulation segments modulated thereon in accordance with a scrambling algorithm;

a plurality of heterodyne receiver channels including a main receiver channel and at least one branch receiver channel said channels including a common carrier phase locked loop local oscillator means including coherent frequency offset means for distributing a separate frequency to each branch receiver, said receiver channels connected to said plurality of antennas, amplifying and converting said carrier signals to a wideband intermediate frequency signal and a narrow band intermediate frequency signal, each one of said plurality of heterodyne receivers having a narrow band output that is phase coherent with each other receiver output;

a first summing junction for combining said output of each of said plurality of heterodyne receivers into a single narrow band carrier signal, coupled to said phase locked loop;

detector means demodulating said wideband intermediate frequency signal from each receiver channel, said detector means having an output;

a second summing junction for combining said wideband demodulated intermediate frequency output of said detector means in said plurality of receiver channels, said junction having an output;

unscrambling means connected to said second summing junction output for unscrambling said wideband demodulated intermediate frequency output of said detector means in accordance with said algorithm; and

means for setting the predetection noise bandwidth of the branch receivers to a value greater than one times the value of the main receiver predetection noise bandwidth;

whereby the carrier sensitivity margin is enhanced in accordance with the number of branch receiver channels and different segments of

the modulation are received on separate frequencies with subsequent unscrambling of the secure communications signals.

8. A frequency diversity receiver as described in claim 7 in combination with polarization diversity wherein said plurality of antennas each includes an orthomode transducer such that the main receiver channel receives one polarization and a branch receiver receives an orthogonal polarization.

9. The method for scrambling data signals for satellite communications, which comprises;

splitting up the data into segments;

multiplexing said segments according to an algorithm having a key;

modulating said multiplexed segments onto a plurality of separate carrier frequencies;

transmitting said multiplexed segments modulated on said carrier;

receiving said plurality of separate carrier frequencies;

heterodyning, amplifying and summing said carrier frequencies; and,

decoding the carriers according to a decoding algorithm usingsaid key, for distribution to authorized users.

10. The method for secure communications of data signals between authorized users as described in claim 9, wherein unrelated data contexts are transmitted on said separate carrier frequencies and separate polarizations, and received on a plurality of summed receiver channels and antennas as described in claim 1.

11. The method for varying the dynamic range of a phase coherent receiver by setting the design level amplitude and noise bandwidth by means of an intermediate frequency filter and increasing the noise bandwidth of the carrier phase locked loop of the coherent receiver in proportion to the amount of limiting.

12. In an array of antennas and heterodyne receiving systems for receiving a modulated carrier, said array having a main receiver and at least one branch receiver, the main receiver having a carrier phase locked loop local oscillator signal distributed to all receivers, producing phase coherent intermediate frequency outputs therefrom, and summing means for combining the outputs to enhance the carrier sensitivity margin, and modulation summing means for combining the demodulated outputs to enhance the modulation signal-to-noise ratio, the improvement, which comprises:

a controller having an input and N outputs for setting the predetection noise bandwidth differential of said at least one branch receiver k times the predetection noise bandwidth of said main receiver, connected to the IF amplifier of the main receiver, at said controller input, and connected to N branch receiver IF amplifiers at the N outputs.

13. The improvement in an array of antennas and heterodyne receiving systems as described in claim 12 wherein the bandwidth differential of said at least one branch receiver is 9 times the bandwidth of said main receiver and said antennas have equal apertures.

14. The improvement in an array of antennas and heterodyne receiving systems as described in claim 12 wherein the bandwidth differential of said at least one branch receiver is 9 times the bandwidth of said main receiver.

15. A receiver as described in claim 1 wherein said plurality of antennas consists of disk-on-rod antennas.

16. A receiver as described in Claim 1 wherein said plurality of antennas consists of paraboloid reflector antennas of the focal point type.

17. A receiver as described in Claim 1 wherein said plurality of antennas consists of offset paraboloid antennas, including shaped reflector antennas.

18. A receiver as described in Claim 1 wherein said plurality of antennas consists of reflector antennas of the cassegrainian type.

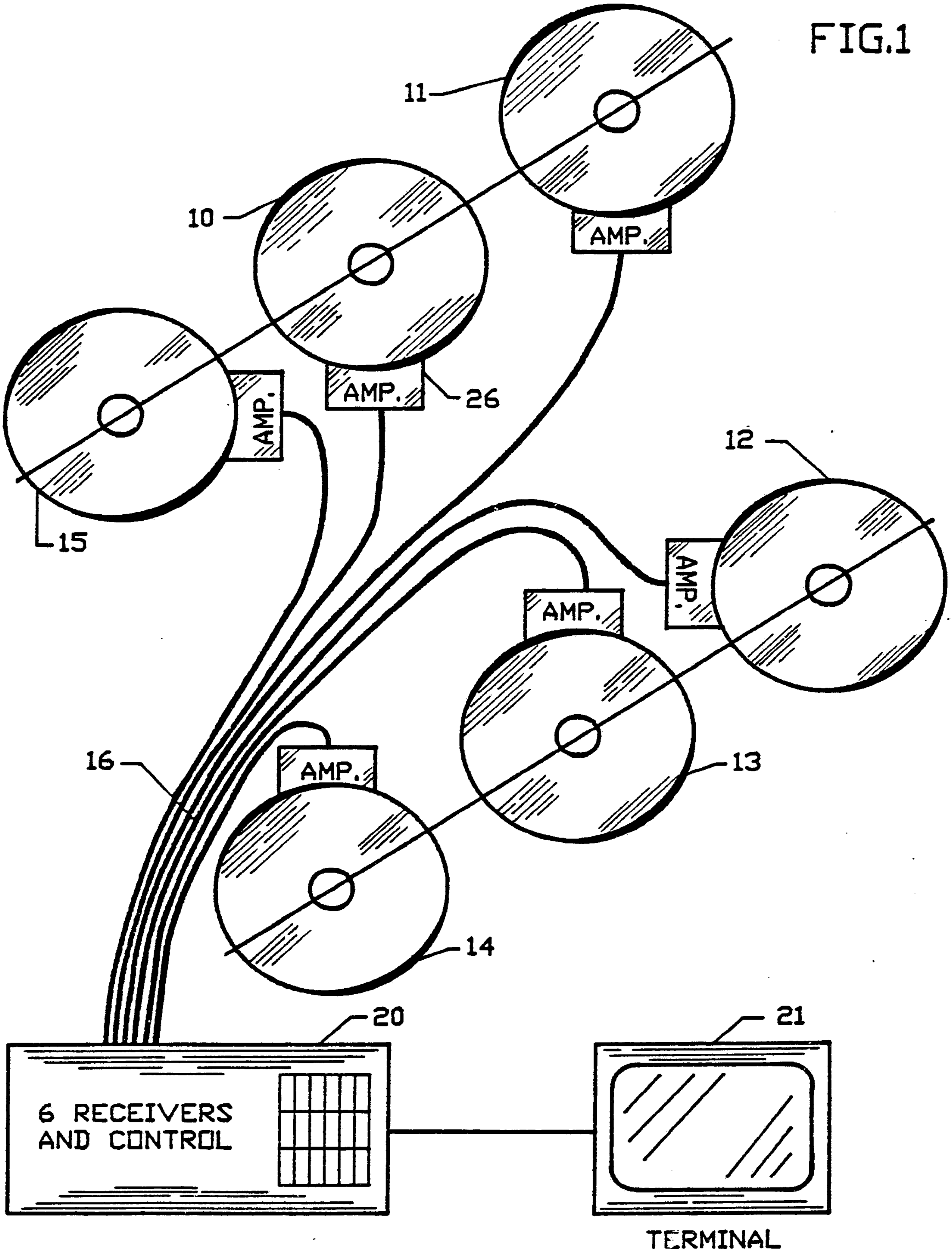
19. A receiver for satellite communications as described in claim 1 wherein said detector means comprises an analog phase detector, an analog tracking filter and a voltage controlled crystal controlled oscillator driving a frequency multiplier to provide the local oscillator and provide a carrier phase tracking loop.

20. A downlink receiver as described in claim 2 wherein said controller means is a bandpass limiter amplifier having a constant power output with varying input signal-to-noise power ratio.

21. A downlink receiver as described in claim 2 wherein said controller means is a total power Automatic Gain Control system producing constant power output with variation in input signal-to-noise power ratio.

22. A downlink receiver as described in claim 2 wherein said controller means comprises means for increasing the open loop gain of the RF carrier phase tracking loop within the region of stable loop operation as the signal component in the limited IF output increases.

FIG.1



11
10
AMP.
AMP.
AMP.
26
15
12
AMP.
AMP.
16
AMP.
13
14
20
21
6 RECEIVERS
AND CONTROL
TERMINAL

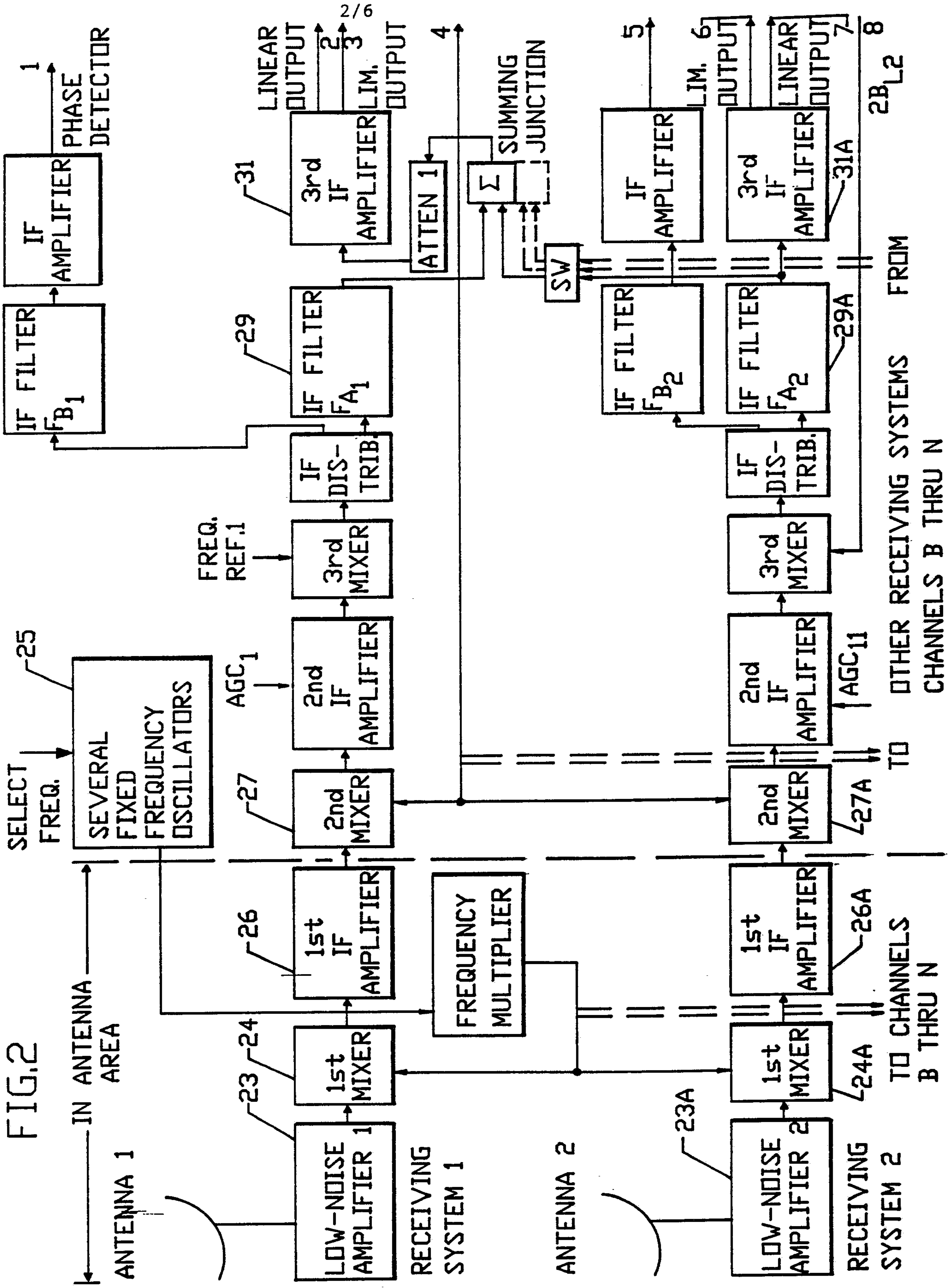
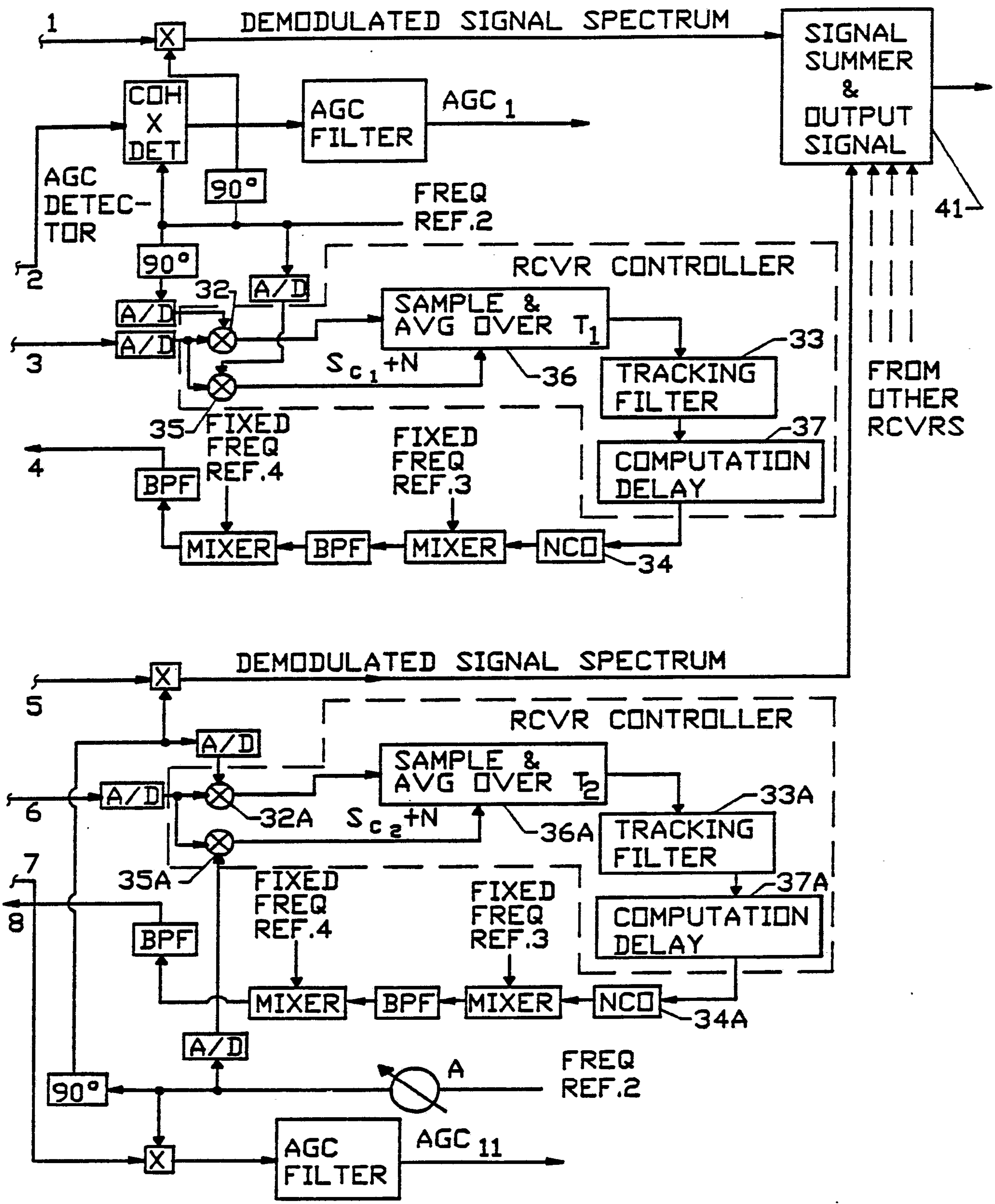

ANTENNA 1
IN ANTENNA AREA
LOW-NOISE AMPLIFIER 1
23
1st MIXER
24
1st IF AMPLIFIER
26
2nd MIXER
27
2nd IF AMPLIFIER
AGC1
3rd MIXER
FREQ. REF.1
IF DIS-TRIB.
IF FILTER FA1
29
3rd IF AMPLIFIER
31
LINEAR OUTPUT
2
3
LIM. OUTPUT
IF FILTER FB1
IF AMPLIFIER
PHASE DETECTOR
1
SELECT FREQ.
SEVERAL FIXED FREQUENCY OSCILLATORS
25
FREQUENCY MULTIPLIER
4
ATTEN 1
Σ
SUMMING JUNCTION
SW
RECEIVING SYSTEM 1
ANTENNA 2
LOW-NOISE AMPLIFIER 2
23A
1st MIXER
24A
1st IF AMPLIFIER
26A
2nd MIXER
27A
2nd IF AMPLIFIER
AGC11
3rd MIXER
IF DIS-TRIB.
IF FILTER FB2
IF FILTER FA2
29A
IF AMPLIFIER
3rd IF AMPLIFIER
31A
5
LIM. OUTPUT
6
LINEAR OUTPUT
7
8
2BL2
RECEIVING SYSTEM 2
TO CHANNELS B THRU N
TO OTHER RECEIVING SYSTEMS CHANNELS B THRU N
FROM

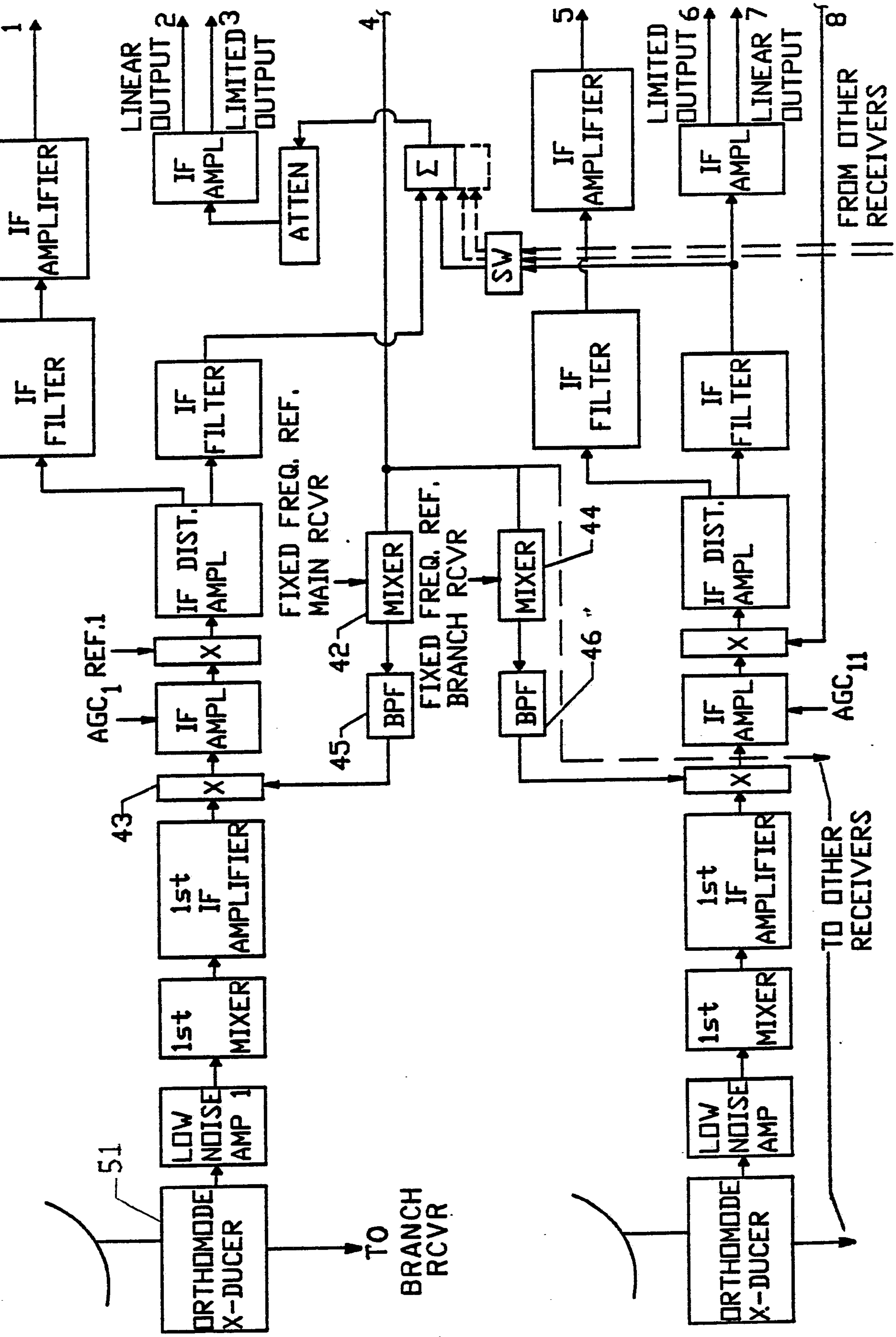
FIG.2



DEMODULATED SIGNAL SPECTRUM
SIGNAL SUMMER & OUTPUT SIGNAL
COH X DET
AGC FILTER
AGC 1
AGC DETECTOR
90°
FREQ REF.2
RCVR CONTROLLER
A/D
SAMPLE & AVG OVER T1
TRACKING FILTER
COMPUTATION DELAY
FIXED FREQ REF.4
FIXED FREQ REF.3
BPF
MIXER
NCO
FROM OTHER RCVRS
1
2
3
4
32
33
34
35
36
37
41
DEMODULATED SIGNAL SPECTRUM
RCVR CONTROLLER
SAMPLE & AVG OVER T2
TRACKING FILTER
COMPUTATION DELAY
FIXED FREQ REF.4
FIXED FREQ REF.3
FREQ REF.2
AGC FILTER
AGC 11
A
5
6
7
8
32A
33A
34A
35A
36A
37A

FIG.3

FIG.4


ORTHOMODE X-DUCER
51
LOW NOISE AMP 1
1st MIXER
1st IF AMPLIFIER
43
X
IF AMPL
AGC1
REF.1
IF DIST. AMPL
IF FILTER
IF AMPLIFIER
1
LINEAR OUTPUT 2
LIMITED OUTPUT 3
ATTEN
Σ
4
SW
TO BRANCH RCVR
FIXED FREQ. REF. MAIN RCVR
MIXER
42
BPF
45
FIXED FREQ. REF. BRANCH RCVR
MIXER
44
BPF
46
ORTHOMODE X-DUCER
LOW NOISE AMP
1st MIXER
1st IF AMPLIFIER
AGC11
5
LIMITED OUTPUT 6
LINEAR OUTPUT 7
8
FROM OTHER RECEIVERS
TO OTHER RECEIVERS

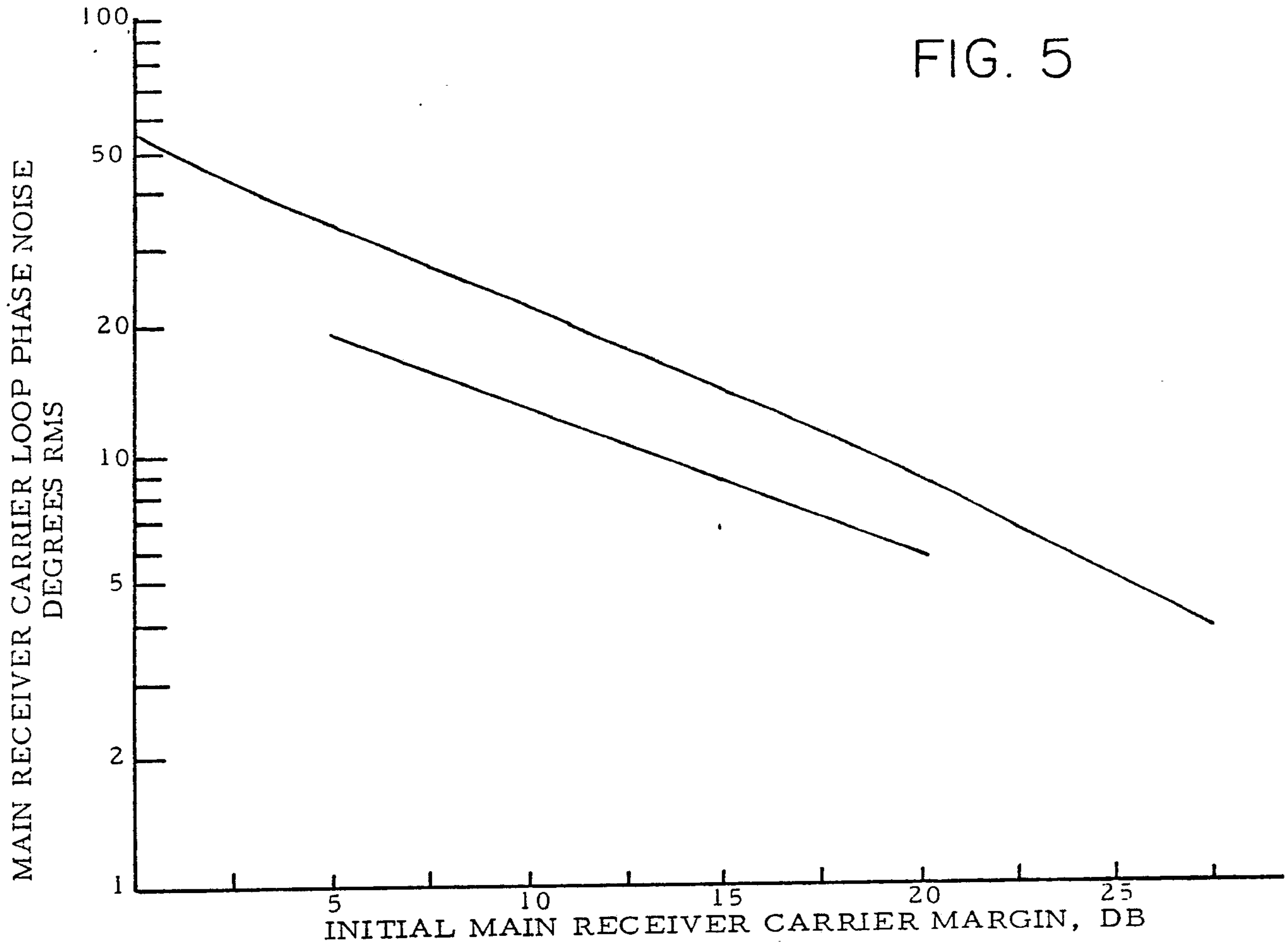

MAIN RECEIVER CARRIER LOOP PHASE NOISE
DEGREES RMS
100
50
20
10
5
2
1
5
10
15
20
25
INITIAL MAIN RECEIVER CARRIER MARGIN, DB

FIG. 5

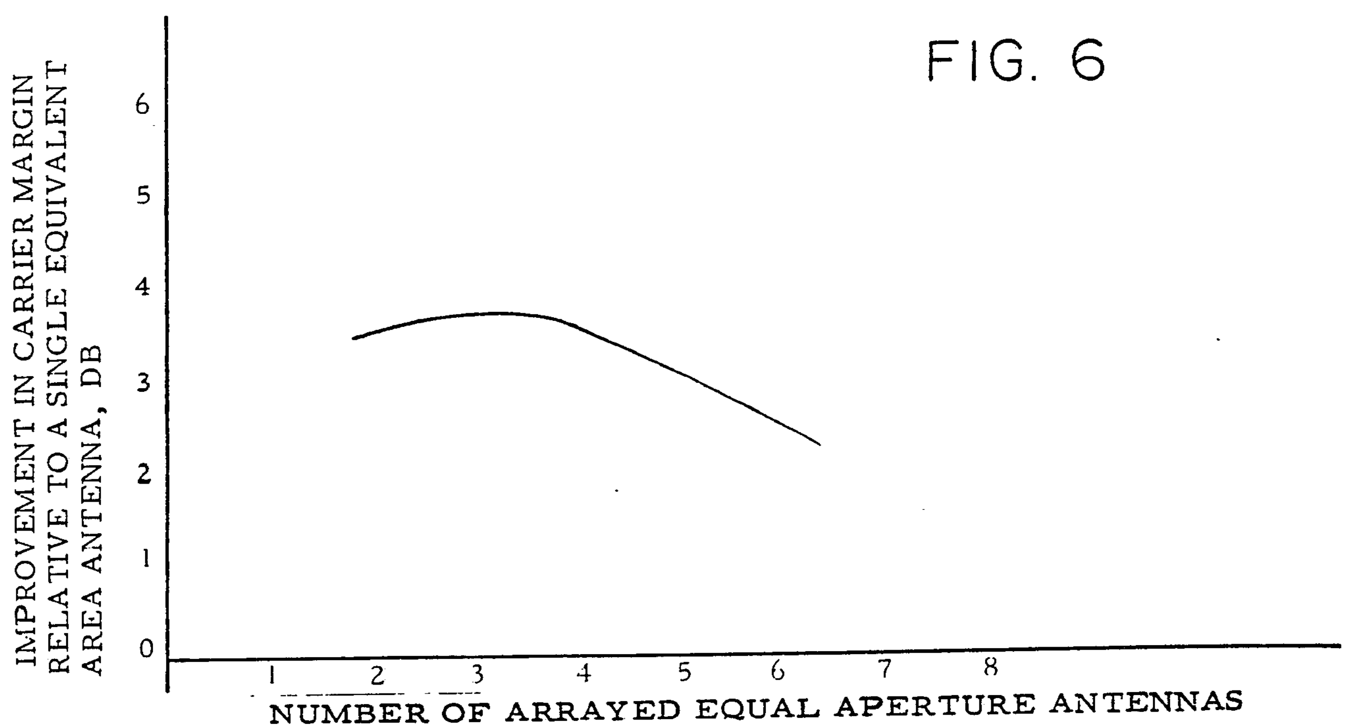

IMPROVEMENT IN CARRIER MARGIN
RELATIVE TO A SINGLE EQUIVALENT
AREA ANTENNA, DB
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
NUMBER OF ARRAYED EQUAL APERTURE ANTENNAS

FIG. 6

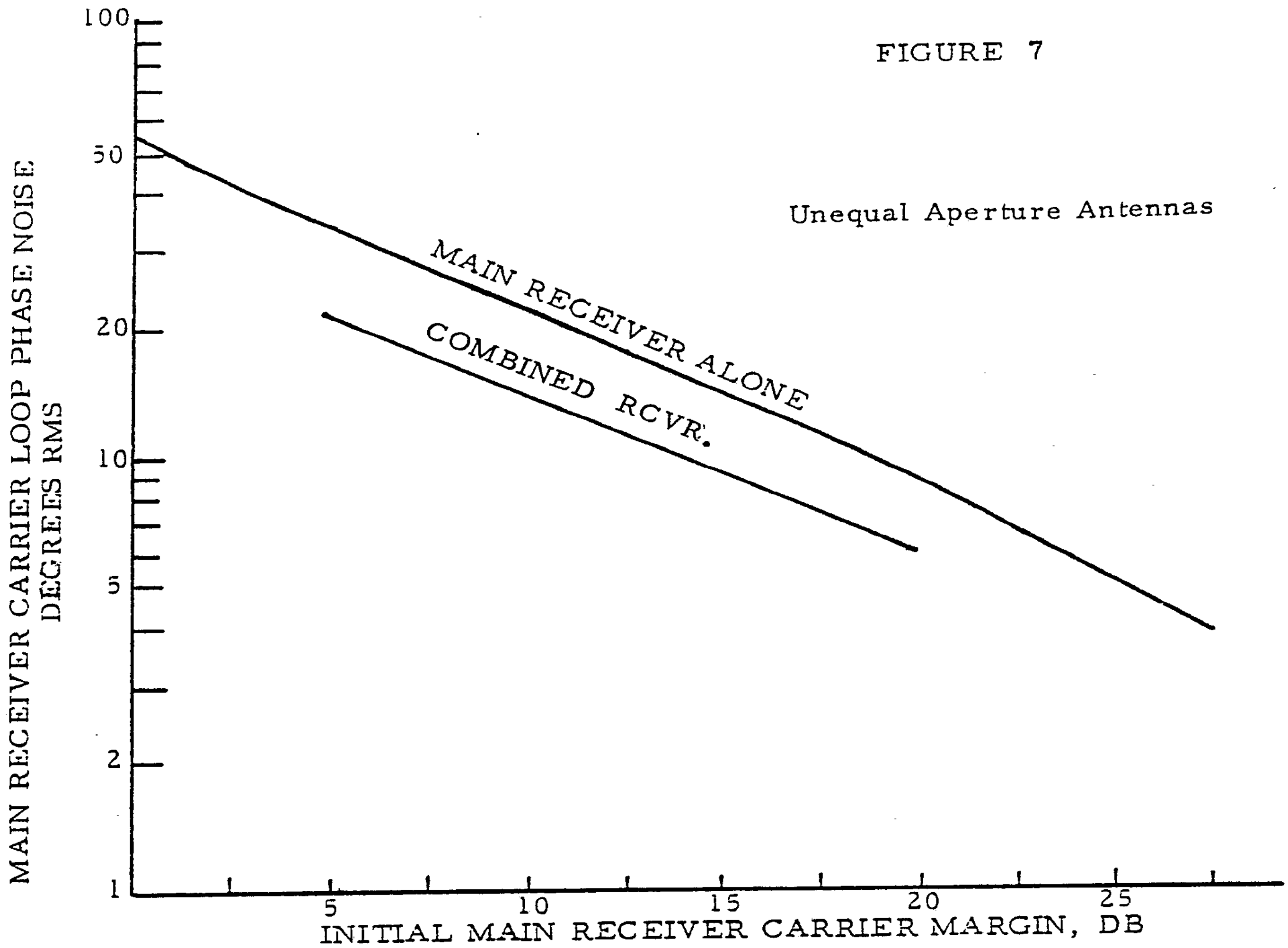


FIGURE 7

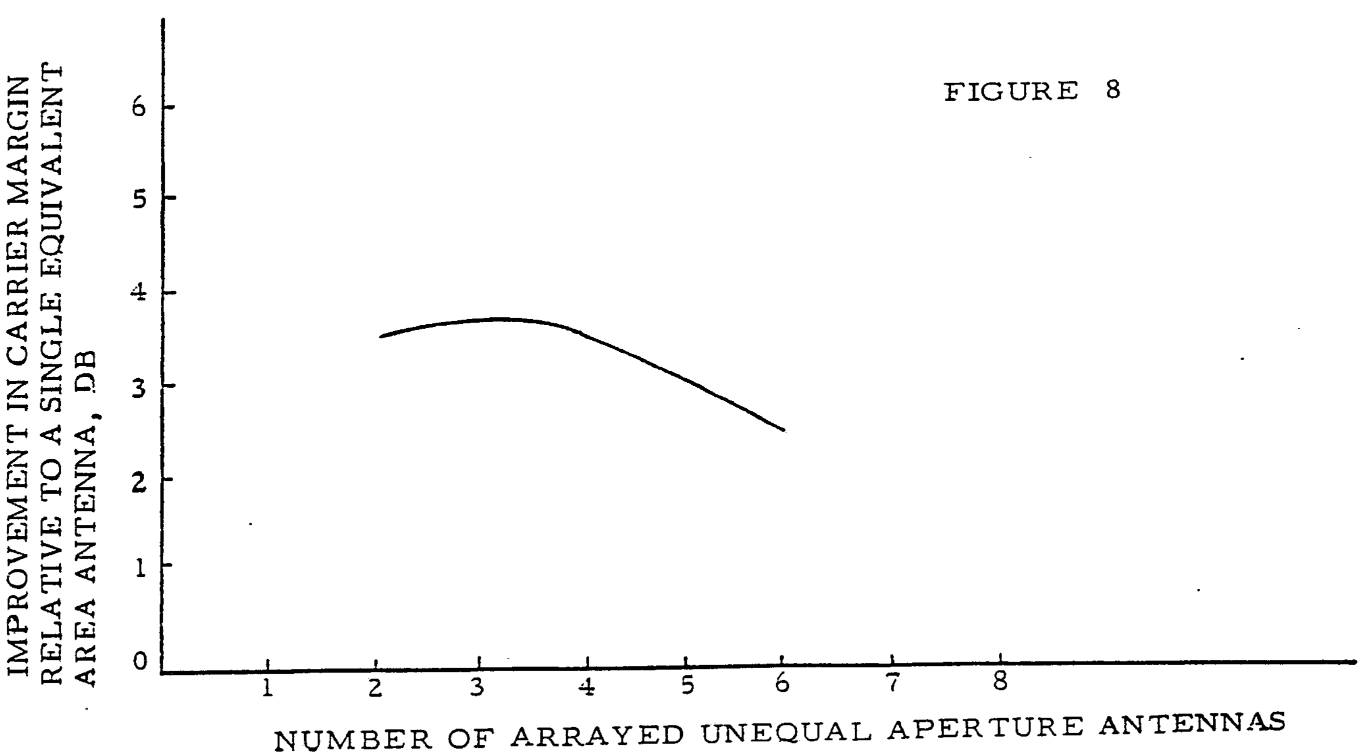


FIGURE 8

INTERNATIONAL SEARCH REPORT

International Application No PCT/US87/00347

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC4. H04L 9/00
U.S. CL. 380/34, 28, 33

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S. CL.	380/34, 28, 33; 375/97, 100; 455/136, 316

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
Y	TDA Progress Report 42-76, October - December 1983, M.H. Brockman, 'Enhanced Radio Frequency Carrier Margin Improvement For An Array of Receiving Systems with Unequal Predetection signal-To-Noise Ratio', (see pages 170-188).	1-22
Y	US, A 4,186,347 Published 29 January 1980 Brockman, et al. (col. 9, lines 14-27; col. 10, lines 17-22; col. 11, lines 17-20)	1-22
Y	US, A, 3,838,342 Published 24 September 1974 Bjorkman (see Abstract)	1-22

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
17 April 1987	30 APR 1987
International Searching Authority [1]	**Signature of Authorized Officer** [20]
ISA/US	Aaron J. Lewis Aaron J. Lewis/pms